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Review of micro/nano machining by utilizing elliptical vibration cutting

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A B S T R A C T

Textured surfaces with sophisticated micro/nano structures can provide interesting and advanced functions. In order to promote those unique functions into the practical use, high performance manufacturing technologies are required. Nowadays, elliptical vibration cutting (EVC) is attracting more and more attentions due to its excellent machining performances, especially the advantageous in the precision machining of difficult-to-cut materials. The emphasis on this literature review is the micro/nano machining technology by applying EVC. The development of the EVC technology is simply introduced, and then the advantageousness of EVC in the machining process is explored in detail. As following, the development of different EVC devices are introduced, and the applications of the micro/nano structure fabrication is detailedly expatiated by applying the different types of elliptical vibrators. By controlling the motion of the ultra-precision machine tool itself, the micro/nano structure can be accurately fabricated on various workpiece materials with the reduction of cutting forces, burr generation, tool wear, et al. in EVC process. Moreover, a unique amplitude control sculpturing method, where the depth of cut is arbitrary changed by controlling the vibration amplitude in the machining process, is introduced. By applying the amplitude control sculpturing method, ultra-precision micro/nano structures can be efficiently sculptured especially on the difficult-to-cut materials. Finally, the elliptical vibration texturing process is also explored in the fast micro/nano machining of the simple and regular structures. The EVC technology is expected to promote the development of micro/nano machining process in the actual industrial applications.

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1. Introduction

Structured surfaces with sophisticated micro/nano structures can provide advanced and useful functions. These micro/nano-structured surfaces can exhibit a number of novel and excellent functions and features as compared with just simple smooth surfaces. To achieve the maximum benefit from the structured surfaces, application technologies of the micro/nano-structured surfaces have been a fascinating research topic in the last few decades. Structured surfaces have been increasingly demanded in various applications, such as optics [1–3], solar energy technology [4–6], bioengineering [7–9], self-cleaning [10,11], advanced manufacturing [12–15], and so on [16,17]. To promote widespread use of the structured surfaces, the manufacturing technology of micro/nano structures for a variety of materials is absolutely essential. When the feature size of the designed structure is downscaled into micrometer or nanometer level, those fabrications may become extremely challenging. To overcome this problem, numerous methods for the micro/nano structure fabrication have been proposed so far. Typical methods are proposed, including the lithographic machining, the laser beam machining, the focused ion beam machining, the electron beam machining, the electrical discharge machining, the diamond machining, and so on.

Lithography, focused ion beam machining and electron beam machining play a critical role in micro/nano-structure fabrication. These processes are advantageous to fabricate highly-dense micro/nano structures with a high aspect ratio and straight sidewalls. The feature size can be downscaled into tens of nanometers or even several nanometers. However, these manufacturing technologies are not available for a large structure height of several hundred micrometers due to their low removal rate and time consuming nature. The machining efficiency is improved by applying the laser machining, however it is difficult to fabricate highly-dense nanometer-scale structures due to the physical restriction in the minimum dimension of focused laser beam. The electrical discharge machining just can be applied to the machining of electrically conductive materials, and the feature size is limited by the geometries of the electrode tool. Considering the mechanical micromachining technologies, micro grinding is not available for dense micro/nano structure fabrication due to the size restriction of grinding wheel, especially the radius of wheel tip. And also, it is difficult to fabricate the sophisticated three-dimensional (3D) structures by applying the micro grinding process. On the other hand, diamond cutting has a large dimension span in the micro/nano structure fabrication, which is flexible and capable for many different designs. Ultra-precision diamond cutting is superior to produce ultra-precision and sophisticated structures in the feature size of several to hundreds micrometers practically. It also has many advantages of high geometrical accuracy, good surface quality and high machining efficiency. Diamond cutting allows a high degree of freedom for the structural design as compared with other methods, and thus it has been widely used especially for plasitic molding applications of a variety of optical elements. Combining with mass production process such as injection molding and compression molding, diamond cutting becomes available for manufacturing of high-quality and low-cost consumer products, and hence, quickly popularizes among the related industries.

Ultra-precision diamond cutting is usually applied to the fabrication of precision parts on plasitic materials, such as the soft metals including oxygen-free copper, brass, aluminum alloy, polymeric material such as PMMA, electroless nickel-phosphorus plating [18], and so on. Recently, ultra-precision dies and molds made of difficult-to-cut materials, i.e., hardened steel and tungsten carbide, are greatly required for the mass production of functional elements with micro/nano structures, especially in optical industry. However, the conventional diamond cutting is not applicable directly to steel materials due to the extremely chemical tool wear [19]. Many researchers have dedicated to attain the conventional diamond machining of steel materials with suppressing tool wear propagation [20–23]. However, none of these methods was found applicable to industrial applications. In addition, tungsten carbide is a typically hard and brittle material, and its ductile machining is extremely difficult by the conventional diamond cutting due to the generations of brittle fracture on machined workpiece surface and the excessive tool damage [24]. On the other hand, micro/nano structured components are mass-produced by glass molding and injection molding with complicated micro/nano structured molds/dies made of hardened steel and tungsten carbide. Hence, advanced diamond cutting technology is highly required for the micro/nano structure fabrication on hardened steel, tungsten carbide, and other difficult-to-cut materials. For the last few decades, ultrasonic vibration cutting technology has been successfully applied to the difficult-to-cut materials machining [25,26]. In particular, Shamoto and Moriwaki [27] proposed a new cutting method named as elliptical vibration cutting (EVC). The feasibility of steel material machining, tungsten carbide machining and several other difficult-to-cut materials machining was verified by applying EVC with the single crystal diamond (SCD) tools. Furthermore, Suzuki et al. [28] proposed a unique micro/nano sculpturing method by controlling the vibration amplitude in the EVC process. It is expected to enable highly-efficient fabrication of sophisticated micro/nano structures on the difficult-to-cut materials. EVC technology is a kind of novel and advanced manufacture technology in the precisely industrial application. It is hoped to be superior to fabricate the micro/nano structures not only on the easy-to-cut materials, but also on the difficult-to-cut materials by applying the SCD tool.

In this review paper, the development of EVC technology is introduced firstly, and then the properties of EVC process are expounded in detail. Moreover, the benefits of micro/nano machining are explored by applying the EVC. Following that, the different types of developed elliptical vibrators, i.e., the non-resonant and the resonant elliptical vibrators, are introduced. And then, the applications of micro/nano structure fabrication are introduced by applying the different elliptical vibrators. The different manufacturing methods for micro/nano structure fabrication, including the slow several of machine tool controlling, the amplitude control sculpturing and the elliptical vibration texturing, are explained in detail. For the ultra-precision micro/nano machining process, EVC is hoped as one of potential superior technologies for the industrial applications.

2. Linear vibration cutting and elliptical vibration cutting

Vibration assisted cutting (VAC) technique is an emerging cutting process that has been increasingly applied in the

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